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# Managing Soil-Water and Chemical Transport with Subsurface Flow Barriers

M. Kiuchi

*United States Department of Agriculture*


Robert Horton Jr.

*Iowa State University, [rhorton@iastate.edu](mailto:rhorton@iastate.edu)*

Tom C. Kaspar

*United States Department of Agriculture, [tom.kaspar@ars.usda.gov](mailto:tom.kaspar@ars.usda.gov)*

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## Abstract

Subsurface water-flow barriers have the potential for reducing  $\text{NO}_3\text{-N}$  leaching and may improve fertilizer-use efficiency in cropping systems. This concept was investigated in field lysimeters near Ames, IA, filled with Sparta loamy fine sand (sandy, mixed mesic Entic Hapludoll) in 1989 and 1990. Our objectives were to determine (i) the effects of subsurface water-flow barriers on leaching losses of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  and on N uptake by corn plants, and (ii) the effects of an absorbent (vermiculite) on the leaching of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$ . Subsurface water-flow barrier treatments were: no barrier (NB), a polyethylene sheet placed above the banded chemicals (PA), a polyethylene sheet placed below the band (PB), and a compacted soil layer formed in situ above the chemicals (CL). In 1989 with corn (*Zea mays* L.) plants growing in the lysimeters, subsurface barriers delayed and reduced leaching and increased plant N uptake compared with NB. The PA treatment was the most effective, reducing  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  leaching by 24 and 21%, respectively, and doubling total N in corn shoots compared with NB. The CL treatment reduced anion leaching by 12%, but did not affect total plant N. In 1990, the subsurface barrier treatments were combined with two application methods, solution banding (S) and solution-vermiculite mixture banding (V). Averaged across barrier types, V banding delayed initial breakthrough of  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  by 1.5 and 2.5 mm, respectively, and reduced the peak anion concentrations by an average of 25% compared with the S banding.

## Disciplines

Agronomy and Crop Sciences | Horticulture | Hydrology | Soil Science

## Comments

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# Managing Soil-Water and Chemical Transport with Subsurface Flow Barriers

M. Kiuchi, T. C. Kaspar, and R. Horton\*

## ABSTRACT

Subsurface water-flow barriers have the potential for reducing  $\text{NO}_3\text{-N}$  leaching and may improve fertilizer-use efficiency in cropping systems. This concept was investigated in field lysimeters near Ames, IA, filled with Sparta loamy fine sand (sandy, mixed mesic Entic Hapludoll) in 1989 and 1990. Our objectives were to determine (i) the effects of subsurface water-flow barriers on leaching losses of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  and on N uptake by corn plants, and (ii) the effects of an absorbent (vermiculite) on the leaching of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$ . Subsurface water-flow barrier treatments were: no barrier (NB), a polyethylene sheet placed above the banded chemicals (PA), a polyethylene sheet placed below the band (PB), and a compacted soil layer formed in situ above the chemicals (CL). In 1989 with corn (*Zea mays* L.) plants growing in the lysimeters, subsurface barriers delayed and reduced leaching and increased plant N uptake compared with NB. The PA treatment was the most effective, reducing  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  leaching by 24 and 21%, respectively, and doubling total N in corn shoots compared with NB. The CL treatment reduced anion leaching by 12%, but did not affect total plant N. In 1990, the subsurface barrier treatments were combined with two application methods, solution banding (S) and solution-vermiculite mixture banding (V). Averaged across barrier types, V banding delayed initial breakthrough of  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  by 1.5 and 2.5 mm, respectively, and reduced the peak anion concentrations by an average of 25% compared with the S banding.

**G**ROUNDWATER is an important natural resource that directly affects many people. In the USA, groundwater is the source of about 22% of the fresh water used. About 53% of the total population and 97% of the rural population use groundwater supplies for their drinking water (Moody, 1990). Although contamination of groundwater can occur naturally, agriculture is considered one of the most widespread nonpoint sources of groundwater contamination. Among all the agricultural chemicals that have the potential to contaminate groundwater, N fertilizer is the most extensively used, especially by corn producers. About one million tons of N fertilizer are used annually in Iowa. In some studies, more than 50% of the applied fertilizer N is not removed by the crop or stored in the soil, and leaching of  $\text{NO}_3\text{-N}$  is thought to be a major reason for these losses (Blackmer, 1987). Nitrate-nitrogen concentrations found in unsaturated soil below the root zone of agricultural fields are in the range of 5 to 100  $\text{mg L}^{-1}$  (Bouwer, 1990). This  $\text{NO}_3\text{-N}$  eventually may enter groundwater supplies. Similarly,  $\text{NO}_3\text{-N}$  concentrations in tile drainage below row crops often exceed 10  $\text{mg L}^{-1}$ , the U.S. drinking-water standard (Gast et al., 1978; Baker and Johnson, 1981; Timmons and Dylla, 1981; Baker et al., 1985).

Nitrate-nitrogen is a water-soluble and nonadsorbed anion. Therefore, the amount of water available for leaching and the chemical concentration (rate of fertilizer applied) at a given time are key factors influencing the leaching loss of  $\text{NO}_3\text{-N}$ . One approach to reduce leaching of  $\text{NO}_3\text{-N}$  is multiple applications of the N fertilizer at reduced rates (Baker and Timmons, 1984; Kanwar et al., 1988). With split fertilizer applications, the concentration of the applied N in the soil profile can be kept at a lower level than with a single, high-rate application. Baker and Timmons (1984) found that multiple applications of N using point injection resulted in greater corn yield than a single application using either deep banding or surface broadcasting of the fertilizer. Similarly, Kanwar et al. (1988) showed that a split fertilizer application with a lower total rate than the rate for the single application reduced  $\text{NO}_3\text{-N}$  concentration in tile drainage without reducing corn yields. Although multiple or split applications of fertilizer may reduce the chemical concentration at a given time, the subsequent application of the fertilizer must be well timed for corn needs. Risks associated with weather and the cost of the fertilizer application must also be considered.

Another approach for reducing  $\text{NO}_3\text{-N}$  leaching is to use surface-soil management to alter flow paths of infiltrating water. Hamlett et al. (1990) showed that the leaching of  $\text{NO}_3\text{-N}$  and  $\text{Br}^-$  placed in the ridge of a ridge-till system was reduced, compared with a flat tillage configuration. The ridge configuration directed excess rain water away from the fertilizer band, toward the furrows. Kay and Baker (1989) also reported that leaching loss of  $\text{NO}_3\text{-N}$  from ridge-till plots was significantly less than from chisel-plowed plots. However, another study did not indicate that ridges had any significant effect on reducing  $\text{NO}_3\text{-N}$  leaching (Bowers et al., 1975). Ridge height and the location of fertilizer N within the ridge should be studied further.

An approach to reducing anion leaching that has not been explored is the use of a subsurface water-flow barrier. Studies have indicated, in theory, that the presence of a localized, impermeable subsurface barrier should direct infiltrating water away from the barrier and reduce the flow rate in the vicinity of the barrier (Maaledj and Malavard, 1973; Babu, 1979; Philip et al., 1989; Kirkham and Horton, 1990). Thus, it is conceivable that  $\text{NO}_3\text{-N}$  leaching could be reduced if the fertilizer is placed in a low-flow region just above or below a barrier.

One way to alter water flow in soil is to compact

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**Abbreviations:** NB, no subsurface barrier; PA, a polyethylene sheet placed above the chemical band; PB, a polyethylene sheet placed below the chemical band; CL, a compacted soil layer formed in situ above the chemical band; CK, check treatment with no subsurface barrier or chemical band; S, banding of solution without vermiculite; V, banding of solution-vermiculite mixture. Combinations of S and V treatments with NB, PA, and CL treatments are abbreviated by combining treatment abbreviations, e.g., SNB, banding of solution without vermiculite with no subsurface barrier.

the soil. Soil compaction destroys the large voids and channels that may readily conduct rainwater in the upper soil profile. The reduced porosity of compacted soil makes it difficult for water to infiltrate (Reicosky et al., 1981; Ankeny et al., 1990). If compaction occurs in localized zones, much of the infiltrating water is directed away from the compacted soil zone and toward more permeable, uncompacted soil. Further, water flow just above and below the compacted soil layer should be reduced. It is, therefore, conceivable that a compacted soil zone will serve as a water flow barrier. Nitrate placed just below a compacted zone of soil is less likely to be immediately carried down by the infiltrating water.

The same principles might be applied to conventional fertilizer banding with a knife applicator. During normal operation, knife applicators create a furrow partly filled with loose soil directly above the fertilizer band. Undoubtedly, the soil above the fertilizer band is very permeable and provides pathways for preferential water flow directly through the band. Therefore, filling in the knife furrow and compacting the soil above the fertilizer band may redirect some of the water flow away from the fertilizer.

Localized compaction zones need not be detrimental to crop growth. First, only a small volume of soil needs to be compacted. Secondly, plant roots are capable of compensating for the reduction of growth caused by unfavorable conditions, such as soil compaction, in part of the root zone by proliferating in more favorable soil zones (Willis et al., 1963; Russell, 1977; Garcia et al., 1988; Kaspar et al., 1991). Thus, it is expected that corn roots can encounter banded fertilizer by growing around a compacted soil zone.

The objectives of this study were to determine in field lysimeters (i) the effects of subsurface water-flow barriers on leaching losses of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  and on N uptake by corn plants, and (ii) the effects of an absorbent (vermiculite) on the leaching of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$ .

## MATERIALS AND METHODS

Transport experiments were conducted in 1989 and 1990 at the Ames rhizotron (Taylor and Böhm, 1976; Klepper and Kaspar, 1994). The Ames rhizotron is a USDA field research facility consisting of 50 lysimeters, each with dimensions of 0.38 by 0.38 by 2.10 m, located 8 km west of Ames, IA. Each lysimeter was filled with Sparta loamy fine sand. The average sand, silt, and clay contents were 82.6, 9.6, and 7.8%, respectively. The bulk density of the soil in the lysimeters ranged from 1.33 to 1.38  $\text{Mg m}^{-3}$  (Stanley, 1978). Each lysimeter had its own drainage system so that effluent samples could be collected from the bottom of each lysimeter separately.

Treatments examined in the 1989 study were: banded  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  with no subsurface barrier (NB), a polyethylene sheet placed above the chemical band (PA), a polyethylene sheet placed below the chemical band (PB), a compacted soil layer formed in situ above the chemical band (CL), and a check (CK), with no subsurface barrier or application of  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$ . Thirty-five lysimeters were divided into seven blocks. Within each block, the five treatments were randomly assigned.

The chemical band contained 20 mL of 7.75 M  $\text{Ca}(\text{NO}_3)_2$  solution (300 kg N  $\text{ha}^{-1}$ ; 4332 mg lysimeter $^{-1}$ ) and 20 mL of

0.2 M  $\text{CaCl}_2$  solution (9.8 kg  $\text{ha}^{-1}$ ; 284 mg lysimeter $^{-1}$ ). The solutions were mixed with 10 g of a commercial, horticultural-grade vermiculite 24 h prior to placement in the lysimeters. Vermiculite was used to absorb the solutions to reduce the drop-out phenomenon caused by the high solution density, which can result in movement of the solution even before leaching begins (Kiuchi et al., 1994).

To position the subsurface barrier, and to band the solution-vermiculite mixture for the PA and CL treatments, a trench, 380 mm long, 150 mm wide, and 100 mm deep, was excavated in each lysimeter. The trench was situated so that it was centered in the lysimeter and its long axis was parallel to the lysimeter drainage tiles. A second trench, 380-mm long, 20-mm wide, and 10-mm deep, was excavated and centered in the bottom of the original trench. The solution-vermiculite mixture was placed in the second trench.

For the PA treatment, a polyethylene sheet, 150 mm wide, was placed flat on the bottom of the original trench over the banded solution-vermiculite mixture and the excavated soil was placed on top. For the CL treatment, some of the excavated soil was scooped back into the trench to a thickness of about 20 mm. Then, about 20 mL of distilled water was sprayed on the soil, and a solid metal cylinder (3.2 kg and 75 mm in diameter) was allowed to fall on the replaced soil 15 times from a height of 100 mm. These processes were repeated a total of three times to form the compacted soil layer. The average bulk density of the compacted soil layer was 1.69  $\text{Mg m}^{-3}$  (SE = 0.022  $\text{Mg m}^{-3}$ ). The remaining excavated soil was then returned to the trench.

For the PB treatment, the original excavation was 110 mm deep. A polyethylene sheet was placed flat on the bottom of the trench, then the excavated soil was scooped back into the trench to form a 10-mm-thick soil layer. The solution-vermiculite mixture was placed in a trench, 20 mm wide and 10 mm deep, excavated from the soil that was placed on top of the polyethylene sheet. The rest of the trench was filled with the excavated soil to restore the original surface configuration. For the NB treatment, a 20-mm-wide trench was made from the soil surface to a depth of 110 mm. The solution-vermiculite mixture was carefully placed at the bottom of the trench, and the trench was refilled with the excavated soil.

Pioneer<sup>1</sup> 3475 hybrid corn seed (Pioneer Hi-Bred International, Johnston, IA) were planted in all of the lysimeters including the CK treatment. Three corn seeds were planted, evenly spaced, 50 mm deep and 50 mm from the side walls, on each side of the band, for a total of six plants per lysimeter. Then, 40 mL of 0.525 M potassium phosphate solution was uniformly distributed on the surface of each lysimeter. One day after planting, the first irrigation of distilled water was uniformly applied to each lysimeter with a sprinkling can. Up to 5 L (34.6 mm) of water were applied to each lysimeter at each irrigation. The amount of water applied at each irrigation was adjusted in response to rainfall, plant growth, and amount of water collected at the previous sampling so that the amount of drainage effluent collected at each sampling was between 0.5 and 1.0 L. The irrigation interval was generally 3 to 4 d and irrigations were continued until 49 d after planting. Drainage effluent was collected at the bottom of each lysimeter throughout the experiment by using a fritted-glass filter and a portable vacuum pump (Long, 1978). The sampling interval was roughly three times a week. After a heavy rainfall, drainage effluent was collected more frequently. The amount of drainage was

<sup>1</sup> Reference to a trade or company name is for specific information only and does not imply approval or recommendation of the company or product by the USDA or Iowa State Univ. to the exclusion of others that may be suitable.

expressed as millimeters, which is based on cubic millimeters of effluent collected divided by lysimeter surface area ( $1.44 \times 10^5 \text{ mm}^2$ ).

Effluent samples were analyzed for  $\text{Cl}^-$  concentration by using colorimetric automatic titration (Adriano and Doner, 1982) and for  $\text{NO}_3\text{-N}$  concentration by using flow injection analysis (Ranger, 1981). The average concentration of the CK treatment at each sampling was subtracted from the measured  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  concentrations of the drainage effluent samples from each lysimeter to correct for the background  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  concentration for determining initial breakthrough, peak concentration, and cumulated drainage at peak concentration. Cumulative leaching losses of anions after 350 mm of drainage were calculated by summing the product of the anion concentration at each sampling time and the volume of water collected and were not corrected for background concentrations.

Plant shoot samples were collected at three different dates. From each lysimeter, three plant shoots were collected at 21 d after planting, another two plants were collected at 38 d after planting, and the final plant was collected at 49 d after planting. All plant samples were dried and analyzed for shoot N concentration using the Kjeldahl method (Bremner and Mulvaney, 1982). Shoot N accumulation was calculated by multiplying shoot dry weight by N concentration.

After drainage ceased, all lysimeters with subsurface barriers and/or solution-vermiculite mixtures were carefully excavated to remove the barriers and vermiculite. At the same time, qualitative observations were made of the position and the orientation of corn roots.

These data were analyzed using an analysis of variance for the randomized complete block design with seven replications. Data for initial breakthrough, peak concentration, and cumulated drainage at peak concentration were analyzed without the CK treatment because it was used to correct for background anion concentrations. Data for shoot N accumulation and cumulative leaching losses at 350 mm of drainage were analyzed with the CK treatment included. Planned orthogonal contrasts were used to partition treatment degrees of freedom. If treatment main effects were significant at the 0.05 probability level, then differences among means were examined using the least significant difference test at the 0.05 probability level. To facilitate data interpretation, breakthrough and cumulative anion leaching curves were also prepared from the drainage effluent data by averaging the anion concentrations and cumulated leaching volumes across replications for each sampling period. Because breakthrough or peak concentration might have occurred during different sampling periods in different lysimeters, even if they had the same treatment, the numbers in the tables and the figures may not match exactly.

In 1990, a similar study of subsurface barrier effects on  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  leaching was conducted by using the same lysimeters, but without the corn plants. Between 1989 and 1990 the lysimeters were allowed to drain freely and were rewet repeatedly by rainfall or irrigation. The purpose of the study was to separate the effects of subsurface barriers from those of the vermiculite absorbent on the leaching of  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$ . The seven treatments considered were a check (CK; no N or  $\text{Cl}^-$  applied) and a factorial combination of two application methods and three subsurface barrier treatments. The application methods were application of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  as a solution (S) or as a solution-vermiculite mixture (V). The three subsurface barrier treatments were NB, PA, and CL, which were three of the four subsurface barrier treatments used in 1989. Thirty-five lysimeters were divided into five blocks. The seven treatments were randomly assigned within each block.

In the 1990 study, 20 g of vermiculite were mixed with 40 mL of 3.875 M  $\text{Ca}(\text{NO}_3)_2$  solution ( $300 \text{ kg N ha}^{-1}$ ;  $4332 \text{ mg lysimeter}^{-1}$ ) and 40 mL of 0.5 M  $\text{CaCl}_2$  solution ( $49.2 \text{ kg Cl}^- \text{ ha}^{-1}$ ;  $1418 \text{ mg lysimeter}^{-1}$ ). For solution banding, 40 mL of 3.875 M  $\text{Ca}(\text{NO}_3)_2$  solution and 40 mL of 0.5 M  $\text{CaCl}_2$  solution were dripped onto the band position as uniformly as possible. The amount of  $\text{Cl}^-$  applied was increased from the amount applied in 1989 to compensate for background levels. The width of the excavated trench and barriers was 0.20 m, otherwise treatments were similar to 1989. After replacing the soil,  $4 \text{ L d}^{-1}$  ( $27.7 \text{ mm d}^{-1}$ ) of distilled water were applied as irrigation to each lysimeter for 3 d using a sprinkling can. Then, drainage effluent sample collection and  $2 \text{ L d}^{-1}$  ( $13.9 \text{ mm d}^{-1}$ ) per lysimeter irrigation were carried out every day for 6 wk. The rate of irrigation was set to maintain approximately  $0.5 \text{ L d}^{-1}$  of drainage effluent. The soil surfaces of all the lysimeters were covered with styrene plates to prevent rainwater from entering lysimeters.

Effluent samples were analyzed for  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  concentrations as in the 1989 study. Also, the average concentration of the CK treatment was used to correct for the background  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  concentration for determining initial breakthrough, peak concentration, and cumulated drainage at peak concentration. Cumulative leaching losses of anions after 400 mm of drainage were calculated and were not corrected for background concentrations.

Statistical analysis of all data was similar to that of the 1989 study. Data were analyzed using an analysis of variance for the randomized complete block design with five replications. Planned orthogonal contrasts were used to partition treatment degrees of freedom. Specifically, comparisons were made between the CK and the other treatments, the two application methods, NB and PA plus CL, PA and CL, and between the effect of the two application methods on the response to the barrier treatments (interaction). Additionally, the LSD test at the 0.05 probability level was used to examine treatment means, if treatment main effects were significant at 0.05 probability level.

## RESULTS AND DISCUSSIONS

### 1989 Study

The initial breakthrough of  $\text{Cl}^-$  was significantly delayed by subsurface flow barriers (PA, PB, and CL) relative to the NB treatment (Table 1, Fig. 1a). Peak concentration of  $\text{Cl}^-$  and the cumulative drainage at the peak concentration were not significantly affected by the treatments, but the peak concentration was numerically higher and the cumulative drainage at the peak was numerically lower for the NB treatment than for the other treatments (Table 1).

Leaching loss of  $\text{Cl}^-$  was significantly reduced when subsurface flow barriers were used (Table 2, Fig. 1b). Among the three barriers tested, a plastic sheet placed above the band (PA) was the most effective subsurface barrier and a compacted soil layer above the band (CL) was the least effective in reducing leaching loss of  $\text{Cl}^-$ . However, all three subsurface flow barrier treatments significantly reduced leaching loss of  $\text{Cl}^-$  compared with NB.

The effect of subsurface flow barriers on initial breakthrough and peak concentration of  $\text{NO}_3\text{-N}$  in the drainage effluent was similar to their effect on  $\text{Cl}^-$  (Table 1, Fig. 2a). The initial breakthrough of  $\text{NO}_3\text{-N}$  was significantly

**Table 1.** Peak concentration of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  in drainage effluent and cumulated drainage at initial breakthrough and at peak concentration in 1989.

Treatment†	Drainage at initial breakthrough		Peak concentration		Drainage at peak concentration	
	$\text{Cl}^-$	$\text{NO}_3\text{-N}$	$\text{Cl}^-$	$\text{NO}_3\text{-N}$	$\text{Cl}^-$	$\text{NO}_3\text{-N}$
	mm	mm	$\text{mg L}^{-1}$	$\text{mg L}^{-1}$	mm	mm
NB	67 b‡	106 b	17.3 a	102.6 a	245 a	249 a
PA	122 a	142 a	12.3 a	82.4 a	268 a	263 a
PB	121 a	140 a	13.6 a	84.6 a	263 a	278 a
CL	100 a	141 a	14.5 a	84.8 a	272 a	272 a

Significance						
Contrasts						
NB vs. Rest	**	**	*	*	NS	NS
CL vs. PA PB	*	NS	NS	NS	NS	NS
PA vs. PB	NS	NS	NS	NS	NS	NS

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively. NS = not significant.

† NB = no barrier, PA = plastic barrier above chemical band, PB = plastic barrier below, and CL = compacted soil layer above.

‡ Means with the same letter within a column are not significantly different ( $P \leq 0.05$ ) according to the LSD test.

delayed by subsurface flow barriers (PA, PB, and CL) relative to the NB treatment. Peak concentrations of  $\text{NO}_3\text{-N}$  and the cumulative drainages at the peak concentration were not significantly affected by the treatments, but the peak concentration was numerically higher and

**Table 2.** Mean cumulative leaching losses of  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  in field lysimeters in 1989 after 350 mm of drainage as affected by subsurface water-flow barriers.

Treatment†	$\text{Cl}^-$	$\text{NO}_3\text{-N}$
	mg	mg
NB	339 a‡	1978 a
PA	276 c	1583 b
PB	291 bc	1756 b
CL	307 b	1752 b
CK	76 d	122 c

Significance		
Contrasts		
CK vs. Rest	**	**
NB vs. PA PB CL	**	**
CL vs. PA PB	**	NS
PA vs. PB	NS	*

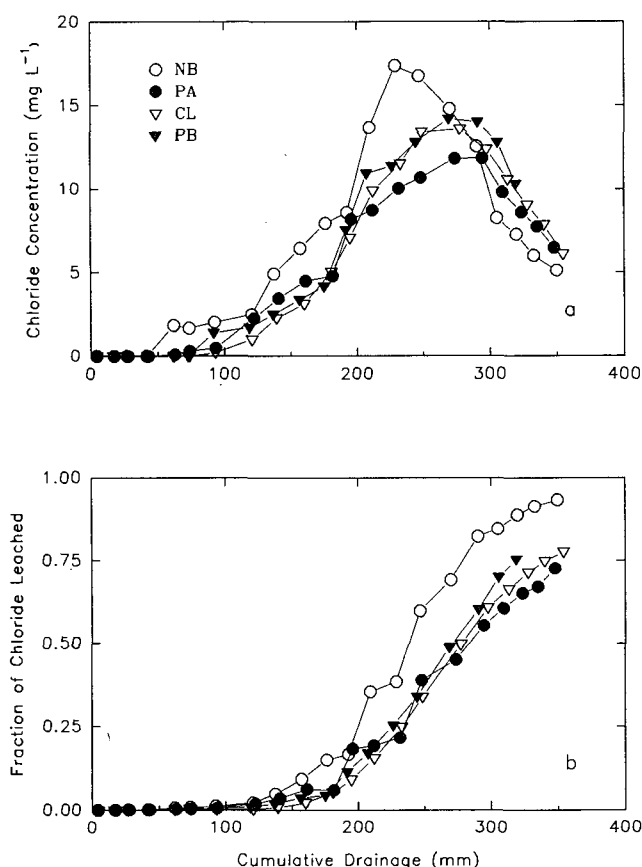
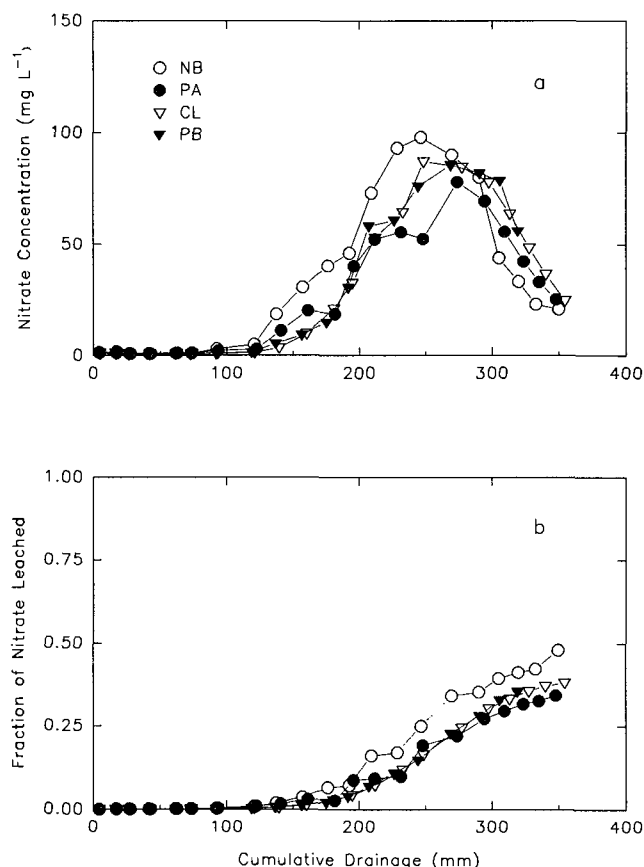
\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively. NS = not significant.

† NB = no barrier, PA = plastic barrier above chemical band, PB = plastic barrier below, CL = compacted soil layer above, and CK = check, no chemicals applied.

‡ Means with same letter within a column are not significantly different ( $P \leq 0.05$ ) according to the LSD test.

the cumulative drainage at the peak was numerically lower for the NB treatment than for the other treatments.

Cumulative leaching loss of  $\text{NO}_3\text{-N}$  after 350 mm of drainage was significantly reduced when subsurface barriers were used (Table 2, Fig. 2b). Contrary to the results of  $\text{Cl}^-$  leaching, there was no statistically significant

**Fig. 1.** Chloride (a) breakthrough curves and (b) cumulative mass fraction of the applied  $\text{Cl}^-$  collected in drainage effluent for subsurface water-flow barrier treatments in field lysimeters with growing corn plants in 1989.**Fig. 2.** Nitrate (a) breakthrough curves and (b) cumulative mass fraction of the applied  $\text{NO}_3\text{-N}$  collected in drainage effluent for subsurface water-flow barrier treatments in field lysimeters with growing corn plants in 1989.

cant difference among the subsurface barriers for the cumulative leaching loss of  $\text{NO}_3\text{-N}$ .

The N content of corn shoot samples was increased by PA and PB treatments (Table 3). At 21 d after planting and 139 mm of cumulative drainage, the PB treatment had the lowest  $\text{NO}_3\text{-N}$  concentration in drainage effluent samples and the smallest fraction of the applied  $\text{NO}_3\text{-N}$  leached out (Fig 2b); therefore more N was found in the shoots. At 38 d after planting and 270 mm of cumulative drainage, shoots from the PA and PB treatments had taken up significantly greater amounts of N than any of the other treatments and this corresponded to lower leaching losses for those treatments than for NB after 270 mm of drainage (Fig. 2b). At 49 d after planting and 305 mm of cumulative drainage, the shoots from the PA treatment had the greatest N content. Over the three sampling dates, corn shoots from the PA and PB treatments accumulated significantly more shoot N than the other treatments. Shoots of corn plants from the CK treatment, which received no N fertilizer, accumulated 122 mg of N. The N accumulated by corn plants in the CK treatment and the 122 mg of N leached from the CK (Table 2) indicates that some mineralization was occurring in all the lysimeters. Thus, a small percentage of the N taken up by corn shoots or collected in the effluent samples probably originated from mineralized N, even in the fertilized treatments.

In general, all of the subsurface barriers delayed and reduced leaching of  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  compared with NB. The PA and PB treatments also increased the N taken up by shoots of corn plants. We hypothesize that an impermeable plastic barrier placed above or below the chemical band protects the applied anions by diverting the flow of infiltrating rain and irrigation water away from the band. In theory, for saturated flow conditions, the slowest flow rates occur just above and below the center of an impermeable subsurface barrier (Maaledj and Malavard, 1973; Babu, 1979; Kirkham and Horton, 1990). This theory may explain why both  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  breakthrough curves for the PA and PB treatment were flatter

**Table 3.** Mean N accumulation in corn shoots at three dates after planting and total N removed from field lysimeters in 1989 as affected by subsurface water-flow barriers.

Treatment†	21 d	38 d	49 d	Total
	mg			
NB	41.0 bc‡	95.7 b	64.3 bc	215.3 bc
PA	49.9 b	183.5 a	178.8 a	412.3 a
PB	68.7 a	164.1 a	110.0 b	342.9 a
CL	44.2 b	95.4 b	90.8 bc	230.4 b
CK	26.0 c	60.4 b	45.6 c	121.6 c
	Significance			
Contrasts				
CK vs. Rest	**	**	**	**
NB vs. PA PB CL	*	**	**	**
CL vs. PA PB	*	**	*	**
PA vs. PB	*	NS	**	NS

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively. NS = not significant.

† NB = no barrier, PA = plastic barrier above chemical band, PB = plastic barrier below, CL = compacted soil layer above, and CK = check, no chemicals applied.

‡ Means with same letter within a column are not significantly different ( $P \leq 0.05$ ) according to the LSD test.

(indicating slower anion leaching) than those of the NB treatment (Fig. 1a and 2a). A prolonged residence time of  $\text{NO}_3\text{-N}$  in the soil profile also should increase N uptake by corn plants, and this was indicated by the data.

Infiltrating water probably moved through the compacted soil layer (CL) more slowly than it moved through surrounding uncompacted soil, but water was not completely blocked by the compacted soil as it was by the plastic barriers. The falling metal cylinder used for compacting the soil did increase the bulk density of the soil layer, but obviously some pores remained that conducted infiltrating water. Thus, the CL treatment was not as effective as the PA and PB treatments in reducing leaching of  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  in this study, as evidenced by the cumulative leaching loss of  $\text{Cl}^-$  after 350 mm of drainage and the corn shoot N uptake. In an earlier laboratory study using soil from the same map unit, but with a slightly lower sand content, a compacted soil layer ( $1.6 \text{ Mg m}^{-3}$ ) was found to be more effective in delaying and reducing the leaching of  $\text{Cl}^-$  than a similar-sized plastic barrier (Kiuchi, 1991; Kiuchi et al., 1994). Thus, although it may not be as effective as plastic, it should be possible, in a moist fine-textured soil, to form a localized, compacted soil layer above banded fertilizer N to divert water around the fertilized soil volume.

Because labeled N was not used and because we could not measure the effect of the applied  $\text{NO}_3\text{-N}$  on N mineralization, it is impossible to actually determine how much of the N found in the drainage effluent and the shoot samples came from the applied N. The recovery of N both in the drainage effluent samples and in the corn shoots was, at most, equivalent to 48% of the applied

**Table 4.** Peak concentration of  $\text{NO}_3\text{-N}$  and  $\text{Cl}^-$  in drainage effluent and cumulated drainage at initial breakthrough and peak concentration in 1990.

Treatment combinations†	Drainage at initial breakthrough		Peak concentration		Drainage at peak concentration	
	$\text{Cl}^-$	$\text{NO}_3\text{-N}$	$\text{Cl}^-$	$\text{NO}_3\text{-N}$	$\text{Cl}^-$	$\text{NO}_3\text{-N}$
	mm		$\text{mg L}^{-1}$		mm	
SNB	7.5 b‡	8.5 c	86.5 a	166.7 a	17.9 a	17.6 c
SPA	11.2 a	11.7 b	56.7 bc	98.8 bc	17.9 a	19.6 bc
SCL	11.1 a	12.5 ab	76.6 ab	115.6 b	20.2 a	20.4 bc
VNB	10.3 a	12.2 ab	64.8 ab	106.1 bc	18.1 a	19.7 bc
VPA	12.3 a	14.5 a	36.2 c	68.1 c	22.8 a	25.3 a
VCL	11.5 a	14.2 ab	68.8 ab	101.3 bc	22.8 a	24.3 ab
	Significance					
Contrasts						
S vs. V	*	**	*	**	NS	**
NB vs.						
PA CL	**	**	*	**	NS	*
CL vs. PA	NS	NS	**	NS	NS	NS
S × V(NB vs.						
PA CL)	NS	NS	NS	NS	NS	NS
S × V(CL vs.						
PA)	NS	NS	NS	NS	NS	NS

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively. NS = not significant.

† S = solution, V = solution-vermiculite mixture, NB = no barrier, PA = plastic barrier above chemical band, PB = plastic barrier below, and CL = compacted soil layer above. Combinations of S and V treatments with NB, PA, and PB are abbreviated by combining abbreviations.

‡ Means with same letter within a column are not significantly different ( $P \leq 0.05$ ) according to the LSD test.

N. Although the fate of the rest of the applied N was not investigated, denitrification, immobilization, and storage in plant roots and soil organic matter are thought to be responsible for the unaccounted N.

Corn roots proliferated in the fertilizer bands even with subsurface barriers in place. Qualitative observations during the post-experiment excavation revealed that corn seminal roots had elongated directly into the fertilizer band for all the treatments. An accumulation of lateral roots just above the barrier for the PB treatment and just below the barrier for the PA treatment was observed. For the CL treatment, no visible seminal or lateral roots were found within the compacted layer of the soil. Instead, roots went around the compacted layer and elongated horizontally toward the band. The compaction and other barrier treatments did not seem to negatively affect the total growth of corn roots or shoots.

### 1990 Study

All of the combinations of solution or vermiculite banding and subsurface barrier treatments significantly delayed initial breakthrough of  $\text{Cl}^-$  relative to that of SNB (Table 4, Fig. 3a and 3c). No other significant differences among treatments for initial  $\text{Cl}^-$  breakthrough were observed. The PA subsurface barrier treatment with either solution (SPA) or vermiculite (VPA) banding reduced the peak concentration of  $\text{Cl}^-$  relative to that

of the SNB treatment combination. The peak concentrations of the SCL, VCL, and VNB treatment combinations were not significantly less than that of the SNB treatment combination, but were greater than that of the VPA treatment combination. Averaged across the three subsurface barrier treatments, vermiculite banding significantly ( $P < 0.05$ ) delayed the initial breakthrough (11.4 mm) and reduced the peak concentration ( $56.6 \text{ mg L}^{-1}$ ) compared with the averages of the solution banding treatments (9.9 mm and  $73.3 \text{ mg L}^{-1}$ ). The occurrence of the peak concentration was not significantly delayed by any of the treatments (Table 4).

The leaching characteristics of  $\text{NO}_3\text{-N}$  were similar in many aspects to those of  $\text{Cl}^-$  for the banding and subsurface barrier treatments. As with  $\text{Cl}^-$ , all treatment combinations significantly delayed initial breakthrough of  $\text{NO}_3\text{-N}$  relative to that of the SNB treatment (Table 4, Fig. 4a and 4c). Additionally, the initial breakthrough for the VPA treatment occurred later than it did for the SPA treatment. All of the treatment combinations reduced the peak  $\text{NO}_3\text{-N}$  concentration relative to the SNB treatment. Other than the SNB treatment, only the SCL treatment also had a significantly higher peak concentration than the VPA treatment. Although none of the treatments delayed the occurrence of the peak  $\text{Cl}^-$  concentration, both the VPA and the VCL treatments delayed the peak  $\text{NO}_3$  concentration relative to the SNB

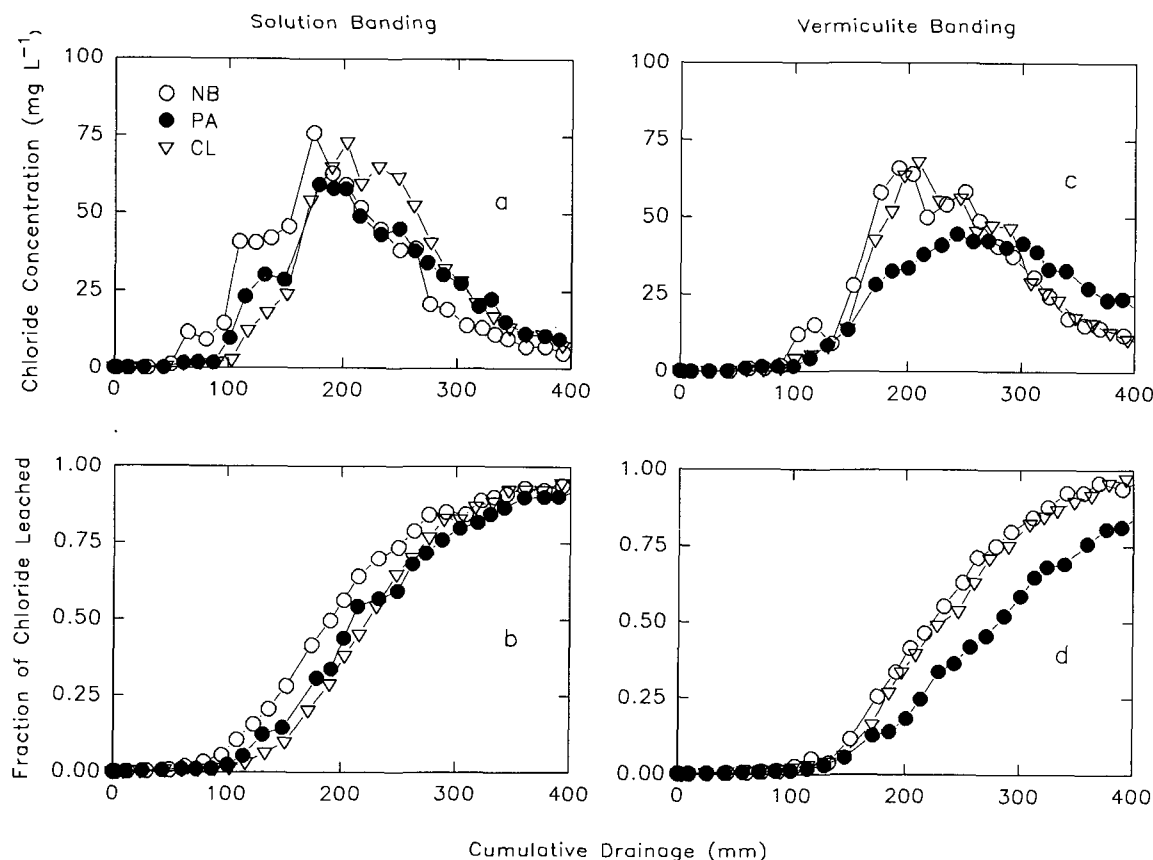


Fig. 3. Chloride (a and c) breakthrough curves and (b and d) cumulative mass fraction of the applied  $\text{Cl}^-$  collected in drainage effluent for combinations of subsurface water-flow barrier treatments and (a and b) solution banding or (c and d) vermiculite banding in field lysimeters in 1990.



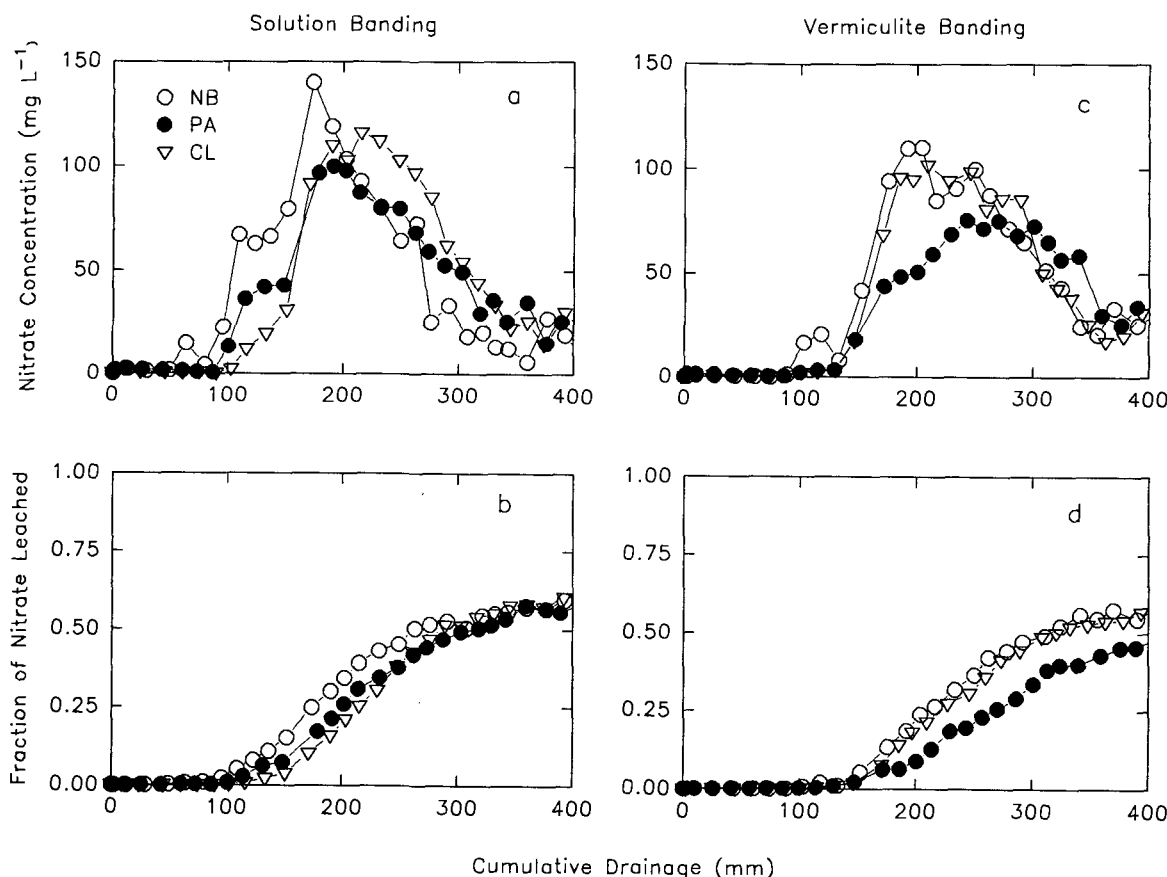


Fig. 4. Nitrate (a and c) breakthrough curves and (b and d) cumulative mass fraction of the applied NO<sub>3</sub>-N collected in drainage effluent for combinations of subsurface water-flow barrier treatments and (a and b) solution banding or (c and d) vermiculite banding in field lysimeters in 1990.

treatment. The peak concentration of the VPA treatment occurred significantly later than those of the SPA, SCL, and VNB treatments. Averaged across the three subsurface barrier treatments, vermiculite banding significantly ( $P = 0.01$ ) delayed the initial breakthrough (13.6 mm) and peak concentration (23.1 mm) and reduced the peak concentration (91.8 mg L<sup>-1</sup>) compared with the averages of the solution banding treatments (10.9 mm, 19.1 mm, and 127.0 mg L<sup>-1</sup>).

In contrast to the 1989 study, the cumulative mass of Cl<sup>-</sup> and NO<sub>3</sub>-N collected in the drainage effluent was affected by only the VPA treatment combination (Table 5, Fig. 3b, 3d, 4b, and 4d). Although intensive irrigation was applied within a short (6-wk) period to create conditions favorable for leaching, about 40% or more of the applied NO<sub>3</sub>-N was not accounted for, whereas almost all of the applied Cl<sup>-</sup> was collected in the drainage effluent samples. The VPA treatment reduced collected cumulative mass of Cl<sup>-</sup> by 11% and of NO<sub>3</sub>-N by 12%.

Apparently, the primary effect of vermiculite was to delay the initial breakthrough of anions (Fig. 3 and 4). Except for the CL treatment, breakthrough curves were shifted to the right when vermiculite was used. One possible explanation is that, when vermiculite was used as an absorbent, the applied Cl<sup>-</sup> and NO<sub>3</sub>-N remained at the original soil depth of the chemical application until water from the irrigations began to flow through the

chemical band. Application of the solution directly, without vermiculite, probably resulted in some downward movement of the denser-than-water solution through the coarse-textured soil immediately after the banding and prior to irrigation (Burns and Dean, 1964; Kiuchi et al., 1994). The vermiculite banding treatment had no effect on peak concentration or on the cumulative mass of Cl<sup>-</sup> and NO<sub>3</sub>-N in the drainage effluent. This seems to indicate that once water began to flow through the vermiculite, the absorbed anions were readily released to the percolating water.

Both Cl<sup>-</sup> and NO<sub>3</sub>-N breakthrough curves for the PA treatment with the solution-vermiculite mixture were flatter than the curves for any other treatment combination (Fig. 3 and 4). Additionally, although the experiment in 1990 was continued until almost all the applied Cl<sup>-</sup> was accounted for and the irrigation rate was greater than in 1989, the VPA treatment combination had a statistically significant decrease in cumulative leaching loss of Cl<sup>-</sup> and NO<sub>3</sub>-N (Table 5). Both these results indicate that when the vermiculite was used to maintain the chemical solution in its original position, the plastic barrier above the chemical band diverted the flow of water enough to slow the rate of anion movement and to improve retention.

The CL treatment showed mixed results in the 1990 experiment. Both the VCL and SCL treatments delayed

**Table 5. Mean cumulative leaching losses of  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  in field lysimeters in 1990 after 400 mm of drainage as affected by subsurface water-flow barriers and chemical banding method.**

Treatment combinations	$\text{Cl}^-$	$\text{NO}_3\text{-N}$
	%	
SNB	1398.9 a <sup>‡</sup>	2822.6 a
SPA	1394.1 a	2742.9 a
SCL	1416.9 a	2837.3 a
VNB	1437.8 a	2775.8 a
VPA	1216.2 b	2261.6 b
VCL	1452.4 a	2513.9 a
CK	59.8 c	174.9 c
	Significance	
Contrasts		
CK vs. Rest	**	**
S vs. V	NS	*
NB vs. PA CL	NS	NS
CL vs. PA	**	**
S × V(NB vs. PA CL)	NS	NS
S × V(CL vs. PA)	**	NS

\*, \*\* Significant at the 0.05 and 0.01 probability levels, respectively. NS = not significant.

<sup>‡</sup> S = solution, V = solution-vermiculite mixture, NB = no barrier, PA = plastic barrier above chemical band, PB = plastic barrier below, CL = compacted soil layer above and CK = check, no chemicals applied. Combinations of S and V treatments with NB, PA, and PB are abbreviated by combining abbreviations.

<sup>‡</sup> Means with same letter within a column are not significantly different ( $P \leq 0.05$ ) according to the LSD test.

initial breakthrough, but did not reduce peak concentrations or cumulative anion mass in the drainage effluent relative to the NB treatment (Fig. 3 and 4, Tables 4 and 5). As in the 1989 study, the compacted soil layer was probably permeable to water and some water moved through the compacted layer and the chemical band below it. For S banding, breakthrough curves for the CL treatment looked similar to those for the NB treatment, but the curves were shifted to the right, indicating a delay in both  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$  leaching. For V banding, the CL and NB treatments resulted in essentially the same breakthrough curves for  $\text{Cl}^-$  and  $\text{NO}_3\text{-N}$ . Apparently, the magnitude of the CL barrier treatment effect was about the same as that of the V banding treatment. One possible explanation for this is that both the soil above the chemical band and the soil containing the applied chemical solution were probably compacted during the imposition of the CL treatment. Like vermiculite, the smaller pore spaces and greater surface area of the compacted soil may have absorbed more of the chemical solution than uncompacted soil, and thus, limited the downward movement of the solution before irrigation began, which would have delayed initial breakthrough.

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